A Low-cost Mobile Infrastructure for Multi-AUV Networking

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***Abstract*— The study of underwater environments is a challenging task that can lead to discoveries in many scientific domains. Among the tools for such studies are Autonomous Underwater Vehicles (AUVs) that can be operated remotely or autonomously for gathering information. The limited communication capabilities of AUVs operating underwater restricts their effectiveness. This paper presents our recent progress towards the development of a modular yet low-cost mobile networking infrastructure for the underwater domain. Specifically, this infrastructure consists of a fleet of autonomous surface vehicles that can serve as a surrogate for research on acoustically connected AUV networks. The work involves the design and development of autonomous surface vehicles and the integration of acoustic communication units to characterize the acoustic communication channel properties when subject to motions of the transmitter or the receiver.**

***Index Terms*— Acoustic Communications; Autonomous Surface Vehicles (ASVs); Autonomous Underwater Vehicles (AUVs).**

I. Introduction

The oceans are dynamic and harsh physical environments requiring a mix of *in-situ* and ad-hoc infrastructures to observe the evolution of physical processes across various spatiotemporal scales. Along with spatially distributed stationary infrastructure, autonomous underwater vehicles (AUVs) are playing an increasing role as underwater sensing systems. To have AUVs perform missions effectively, they require robust communications with collaborating underwater, surface, and terrestrial systems. Below the water surface, acoustic communications is one promising technique that allows coordination, remote command and control, trajectory planning, and positioning of underwater systems [1], [2].

Underwater acoustic (UWA) communications have been challenged by the characteristics of UWA channels, such as large spatiotemporal channel dynamics, low sound speed in water, and abundant interferences [2], [3]. Furthermore, the motion of either the transmitter or the receiver can result in distortion of the communication waveform leading to poor or unreliable transfer of data packets [4], [5]. Characterization of mobile UWA channels can broaden the application of this communication technique on AUVs and other mobile underwater vehicles. Existing studies have mainly been constrained to "controlled" systems where the acoustic communication unit is equipped on large-size human-operated mobile platforms (e.g., research vessels) [4], [5]. The challenges associated with mobile UWA communications in light-weight and small-size autonomous vehicles have not been well demonstrated. One goal of this work is to reveal the fundamental challenges of mobile UWA communications among AUVs. Here, we focus on the orthogonal frequency-division multiplexing (OFDM) technique [6], which has been widely used for high-rate radio communications.

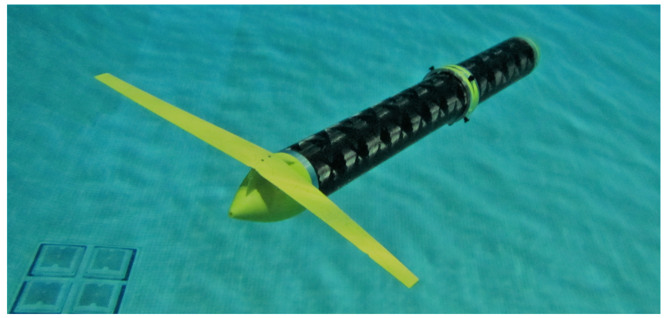

Fig. 1. Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) developed by NASLab as long-endurance AUV.

Currently available acoustic transmitters are large and heavy compared to the payload that small, research-oriented AUVs can carry. This leads to challenges in development and experimentation of underwater communication networks for AUVs. To overcome this challenge, one approach can be the use of other mobile platforms such as autonomous boats as surrogate vehicles. Autonomous Surface Vehicles (ASVs) have demonstrated to be capable platforms for carrying payloads in scientific efforts such as environmental sampling and environmental monitoring while carrying a range of sensors in oceans [7]–[11]. Other applications include maritime security [12]–[15] and ocean observation [16], [17]. These efforts demonstrate the reliability and suitability of ASVs for addressing tasks in harsh and unpredictable marine environments. Control and navigation of these vehicles has been studied extensively [18]–[20]. ASVs with integrated acoustic communication modules can serve as mobile networking infrastructure. Although a number of efforts have resulted in

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development of off-the-shelf ASVs, these vehicles are often mission-specific, costly, and have closed architectures.

To better address the development required for this project, we built a fleet of autonomous surface vehicles that are low-cost, easily deployable to minimize the logistical overhead, and provide the opportunity for modification on any level of hardware and software. Then, we integrated communication modems with the ASVs and characterize the UWA communication performance through field testing. The efforts will result in an infrastructure and advanced algorithms for more efficient and reliable underwater mobile communication networking.

A long-term goal of this research is to reveal and tackle fundamental challenges for seamless integration of acoustic communication modules with AUVs. Following these efforts, we will extend the work to communications between underwater gliders. A fleet of custom-made low-cost modular underwater gliders called ROUGHIE developed by the NASLab at Michigan Tech will be equipped with acoustic communication modems for wireless information transfer and underwater localization (Fig. 1) [21], [22].

This paper describes the current stage of our development and findings, and will serve as a proof of concept for mobile underwater acoustic networking. The rest of the paper is organized as follows. Section II presents our discoveries in a mobile UWA communication experiment using manned vessel. Section III describes the development of autonomous boats that will provide the mobility to the communication network and preliminary testing results of the integrated system. Section IV concludes with the discoveries and lays the path for future works.

II. Performance Study of Mobile Underwater Acoustic Communications

To study the characteristics of mobile UWA communications, we conducted an experiment in Lily Pond, located just off of Lake Superior near Houghton, Michigan. The experiment consisted of four static nodes and a mobile node. As illustrated in Figs. 2 and 3, the four static nodes were anchored at locations A, B, E and F. The mobile node was towed by a human-operated boat at an average speed of around 1 m/s and traveled back-and-forth between Site A and Site B. The water depth of the experiment area is around 8 meters, and the distance between Site A and Site B is 765 meters. During the towing process, the mobile node transmitted a 4-second long communication waveform every 15 seconds at a power level of 0.3 Watts. The four static nodes served as receivers. The communication waveform has a carrier frequency of 24 kHz with a bandwidth of 6 kHz. Besides the preamble and postamble, the waveform consists of a single transmission data block modulated by the OFDM technique [6] and a rate-$1/2$ non-binary low-density parity-check (LDPC) code with an overall transmission rate of 2,688 bits/second.

To reveal the insights of UWA mobile communications, we focus on the received waveforms at Node E when the mobile transmitter travels from Site A to Site B, and present some of the processed results.

Fig. 2. Deployment locations for Lily Pond test on satellite map.

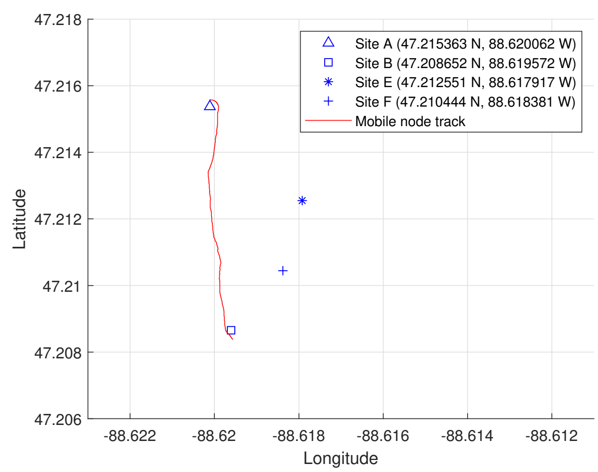

Fig. 3. Trajectory of the mobile node in the Lily Pond experiment.

A. Doppler effect analysis

Due to the low sound speed in water, the movement of the transmitter causes compression or dilation of the communication waveform. Such a Doppler effect needs to be carefully considered while processing the received data. The Doppler scaling factor a is computed as $a = v/c$, where v is the transmitter node's moving speed with respect to Node E, and $c \approx 1,450$ m/s is the sound speed in water. In this experiment, the estimated Doppler scaling factor based on the received waveforms at Node E is shown in Fig. 4. One can observe the change of the Doppler scaling factor when the transmitting modem gets near to Node E and then moves

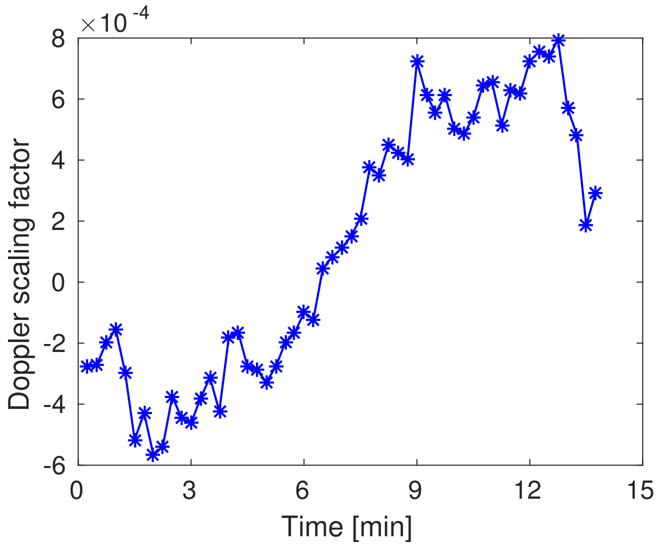

Fig. 4. The estimated Doppler scaling factor as the transmitter moves from Site A to Site B.

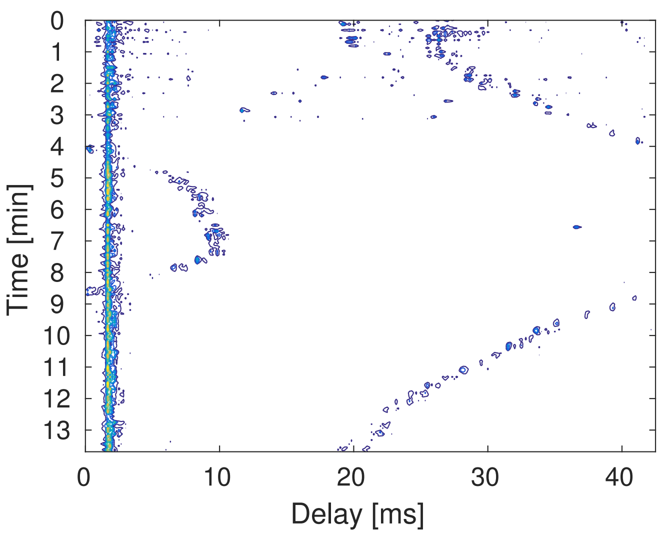

Fig. 5. The estimated UWA channel as the transmitter moves from Site A to Site B. A horizontal slice represents the channel impulse response, where the magnitude is color coded.

away from it.

B. Mobile channel estimation results

For each acoustic transmission, the UWA channel impulse response (i.e., the multipath information) can be estimated via a least squares approach [6]. The evolution of the UWA channel estimation as the transmitter node moves from Site A to Site B is plotted in Fig. 5. One can observe an interesting change of the channel multipath structure (especially the latter arrivals) at Node E.

C. Mobile communication decoding results

The decoded results at Node E corresponding to all the transmissions are shown in Fig. 6. During receiver processing only two transmissions have non-zero bit error rates (around 0.15 of bit error rate) with the LDPC coding for error

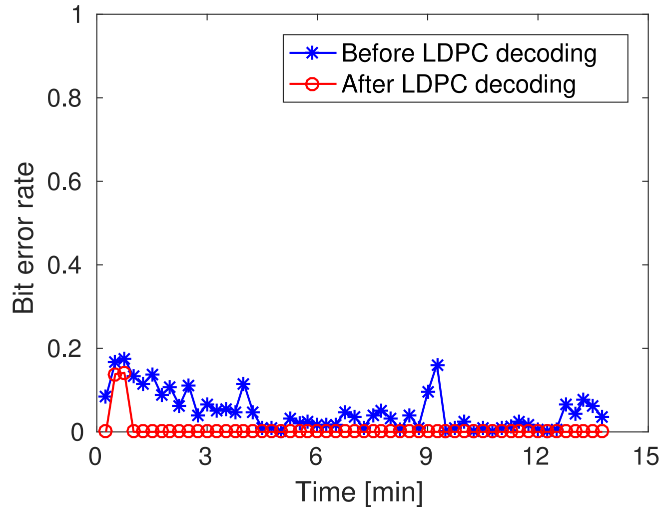

Fig. 6. The decoded bit error rate as the transmitter moves from Site A to Site B.

Fig. 7. Image of an autonomous surface vehicle developed for establishing an underwater communication infrastructure.

correction. The information bits in all the other transmissions can be successfully decoded. To reveal the change of the communication performance as the transmitter node moves from Site A to Site B, we also plot in Fig. 6 the bit error rate of each transmission without the use of the LDPC coding. One can see that the communication performance improves as the transmitter moves near to Node E and degrades slightly as the transmitter moves away from it.

III. Developing Autonomous Mobile Underwater Acoustic Communication Nodes

To establish an acoustic communication network, the communication modules should maintain a spatiotemporal configuration that allows reliable communications between the AUVs. To provide mobility and autonomy for the communication modules, Michigan Tech's NASLab is working on developing a fleet of of low-cost modular ASVs. Each

ASV will be equipped with a custom autonomy package and the required sensors for accurate and adaptable navigation in complex environments with the ability to integrate other sensors on an as needed basis.

A. Development of autonomous surface vehicles

Each ASV platform comprises of a 3 meter inflatable dingy paired with a transom-mount electric trolling motor that provides actuation to the system (Fig. 7). In addition to the main thrust motor, a secondary actuator controls the steering of the motor. By changing the direction of the thrust vector using the secondary actuator, it is possible to modify the heading of the vehicle. For compatibility with added components, the original controllers of the motor have been replaced with electronic speed controllers designed for driving brushed DC motors. The controllers are connected to deep cycle batteries for long duration operation.

The vehicle controller uses information from multiple onboard sensors for decision making. An encoder has been added within the motor to measure the heading of the motor with relation to the vehicle's body. A Bosch BNO055 Inertial Measurement Unit (IMU) is installed on the motor to measure the heading of the motor and consequently the vehicle's heading with relation to magnetic north pole. A Ublox NEO-7P GPS provides information on the location of the vehicle to calculate the distance and desired bearing to reach waypoints. The data from all the sensors is collected by an Odroid XU4 single-board computer. The computer performs control calculations using sensor data and outputs actuation commands to the motor's two speed controllers. To configure the mission and monitor the platform during operation, the onboard computer communicates with a user computer through a RFD900 telemetry radio. An interface developed for the user computer allows the user to configure mission waypoints on top of satellite images. This interface also enables the user to remotely operate the vehicle using a Xbox controller. The control commands of the Xbox controller are sent to the ASV via the telemetry radios. Specifics of the components and their communication protocols are illustrated in Fig. 8.

Control of the ASV is based on a pure-pursuit method (Fig. 9). In this method, an imaginary line is drawn between the start point and the destination. A point is found on this line with a specified distance ahead of the vehicle. The vehicle then adjusts its heading to drive toward this point. The pure-pursuit algorithm implemented on the ASVs modulates its lookahead distance based on the cross-track error of the vehicle from the desired path line. The lookahead distance becomes shorter as the vehicle's cross-track error grows. This control algorithm outputs the desired heading for the vehicle. The real heading of the vehicle is also gathered from the motor's steering angle and IMU's heading relative to north. The error between desired heading and the real heading is sent to two nested PID loops. The first PID loop uses this error to generate a steering command to minimize the heading error. The second PID produces the motor's angle relative to the vehicle's body to achieve the steering.

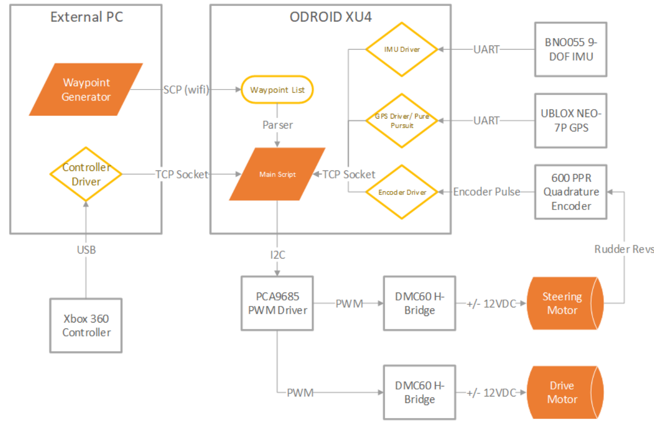

Fig. 8. Components and protocols involved in gathering information from sensors and sending commands to the motor.

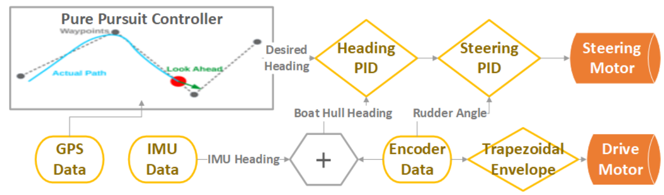

Fig. 9. ASV Control system navigates the vehicle to assigned waypoints.

Due to the light weight of the vehicles, applying high throttle values when the motor is at extreme angles leads to high angular acceleration of the body, followed by undesirable overshoots. To prevent such overshoots, the throttle of the ASV is modulated via a trapezoidal profile that reduces the throttle when the motor is at extreme angles relative the vehicle's body.

The described modification to the simple pure-pursuit method resulted in reducing the cross-track error significantly. The performance characteristics of the ASV are presented in Table I. During testing, the ASV was able to maintain course while subjected to 0.6 meter waves.

TABLE I
PERFORMANCE CHARACTERISTICS OF THE ASV IN AUTONOMOUS OPERATION MODE.

Property	Value
Maximum Speed (m/s)	2.0
Tracking Error (geographical degrees)	3.8e-5
Tracking Error (meters)	3.5
Tested Wave Height (meters)	0.6

B. Integration of acoustic communication modules with ASVs

Each ASV is equipped with an AquaSeNT OFDM acoustic communication modem (Fig. 10) [23]. This will create a low-cost mobile infrastructure for underwater mobile acoustic communications and networking.

We identified two methods of physically integrating the modems with the ASVs. One way is to fabricate a housing

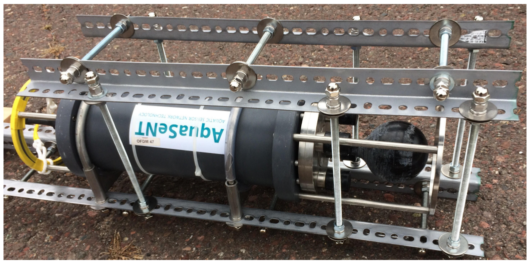

Fig. 10. The underwater acoustic OFDM modem, installed in a protective housing.

for the modem and rigidly install the housing on the vehicle (Fig 10). This approach allows the modem to stay nearly vertical in water to maximize its signal range and keep the connection characteristics relatively consistent during the operation. We observed two drawbacks when experimented with rigid installation of the modem on the vehicle due to the significant drag force exerted on the housing structure. One problem was the large amount of variable forces due to drag fatigued the structural connection between the vehicle and housing structure. The other issue was that this addition to the shape of the vehicle drastically changed the dynamics and maneuverability of the ASV. The other integration approach identified was tethering the modem by connecting it to the vehicle using a cable. This approach does not pose the same challenges as rigid mount but subjects the modem to greater risk as it is freely moving in the vicinity of the vehicle. The preliminary tests of tethering the modem has been successfully performed using a manually driven boat as presented in section II. This method will be further evaluated using the ASVs in future testing opportunities.

C. Preliminary testing results of the integrated system

We conducted a preliminary test in Portage Lake to evaluate the communication performance between an acoustic modem rigidly installed on an ASV and an anchored static node. As depicted in Figs. 11 and 12, the moving modem transmitted a 4-second long acoustic communication waveform every 10 seconds while traveling along a predetermined line trajectory at an average speed of 0.67 m/s. The static node served as a receiver. The trajectory of the ASV was nearly 500 meters long, and the horizontal distance between the static node and the ASV track is about 200 meters. The water depth in the experiment area is around 10 meters. In this test, due to a very low transmit power of 0.03 Watts, the received waveform at the static node does not have a sufficient signal-to-noise ratio for successful decoding. Nevertheless, the received waveform allowed a fairly good estimation of the Doppler scaling factor (namely, the waveform compression or dilation rate) at the static node. The estimation of the Doppler scaling factor as the transmitting ASV navigates along the line trajectory is depicted in Fig. 13. Comparing Fig. 13 with Fig. 4, one can see that the ASV could introduce more variation in the Doppler effect than the human-operated boat, primarily due to the light weight of the vehicle that magnifies the disturbance incurred by the

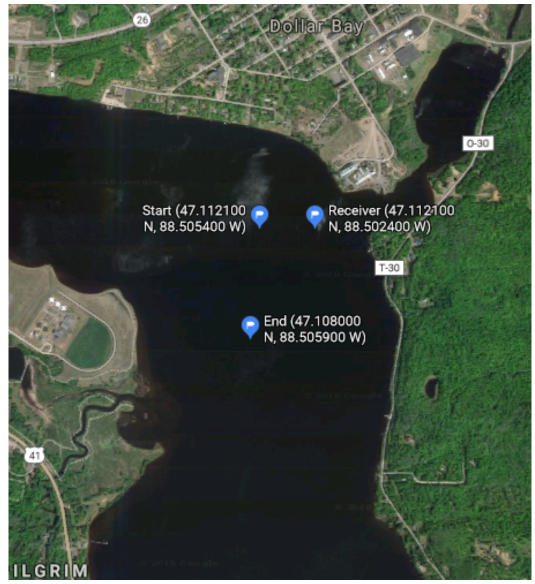

Fig. 11. Deployment locations for Portage Lake test on satellite map.

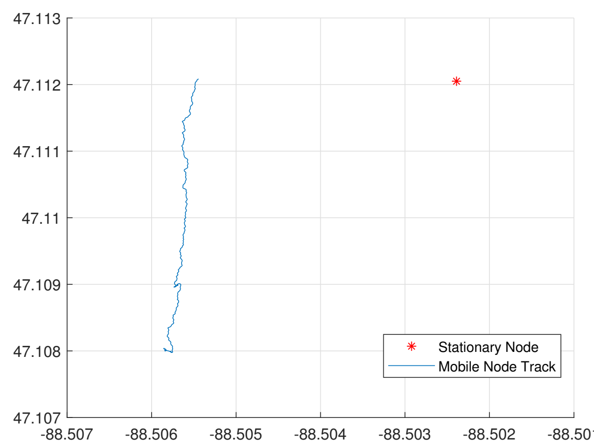

Fig. 12. The real trajectory of the ASV during the Portage Lake test.

water current.

IV. Conclusion and Future Works

This paper presented our road map and the current state of progress for developing a low-cost and modular mobile underwater communication network infrastructure. The work involves the design and development of ASVs and integration of acoustic modems with the ASVs for field experimentation. To this stage of development, the ASVs have been constructed and their waypoint navigation functionality is validated. Additionally, field experiments were conducted to reveal the challenges in mobile UWA communications and to evaluate the integration of the acoustic modem with the developed ASV. The experimental data analysis demonstrated the evolution of the communication performance during the movement of a transmit node. The change to the mobile channel multipath structure could lead to new research opportunities for channel modeling. Furthermore, the preliminary test of the integrated system showed that

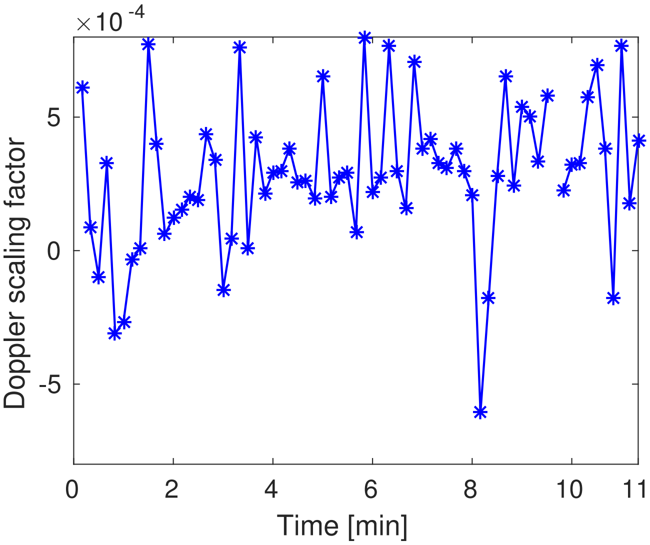

Fig. 13. The estimated Doppler scaling factor as the transmit ASV travels along a predetermined track.

acoustic communications on AUVs could suffer from more highly varying Doppler effect than those on human-operating mobile platforms.

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